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Nanostrain Measurement Using Chirped Bragg Grating Fabry-Perot Interferometer

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Abstract: A simple nanostrain direct current (DC) measurement system based on a chirped Bragg grating Fabry-Perot (FP) structure is presented. The FP cavity, formed between the chirped fiber Bragg grating (CFBG) and the fiber end face, presents an aperiodic behavior due to the CFBG. A laser located in the fringe pattern slope is used to interrogate the sensing head. The optical power parameter is analyzed when strain is applied, for long and short period fringe pattern wavelengths, and sensitivities of –2.87 μW/με and –5.48 μW/με are respectively obtained. This configuration presents a resolution of 70 nε.

Keywords: Optical fiber sensor, Fabry-Perot interferometer, chirped fiber Bragg grating

1. Introduction

Nanostrain measurement can be useful in specific applications such as geophysics engineering. Nowadays, the characterization of earth deformation is made using conventional sensors. An alternative solution is the utilization of optical sensors. There are several works about dynamic fiber Bragg grating (FBG) strain sensors, in which very high resolutions are reported. Kersey *et al.* [1] investigated a technique for the detection of dynamic strain induced wavelength shifts in FBG sensors. This technique is based on an unbalanced interferometer wavelength discriminator, which is capable of subnanostrain resolution (0.6 nε/√Hz at 500 Hz) sensing. Two different approaches were done by Ferreira *et al.* [2], the serrodyne and dithering techniques, with resolutions of 2 nε/√Hz and 3.3 nε/√Hz, respectively. Regarding dither demodulation, temperature and strain measurements were made for a frequency of a few hertz. The sensitivities obtained were 0.09 ℃/√Hz and 0.6 με/√Hz, respectively [2]. Another technique to measure nanostrain is based on a frequency locked laser [3]. Using this technique for low frequency measurement, the sensitivity obtained is 1.2 nε/√Hz. The mentioned configurations require equipment or signal processing of high complexity. Besides, all measurements are made using alternating current (AC) signals above 1 Hz. These configurations can be simplified by optimizing the sensing head. In order to solve this issue, a reduction of the FBG bandwidth is needed [4]. A simple solution is to fabricate a Fabry-Perot (FP) cavity inside the spectral response of the Bragg grating. The FP cavity can be formed by placing two FBGs in series [5], or combining a FBG with the cleaved end of the fiber tip [6]. The chirped FBG has a large spectral response due to the chirp behavior, consequence of varying the grating period or the effective refractive

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index change along the FBG length. Several techniques for fabricating chirped gratings have been demonstrated, particularly by considering methods based on temperature and strain gradients [7], or by writing an FBG structure in a tapered core fiber [8, 9]. These structures are recognized to be important in optical communication for dispersion compensation [10], however, they can also be used as strain sensing elements [11], strain and temperature discrimination [12] and as a part of interrogation schemes [13]. In this work, a simple chirped fiber Bragg grating Fabry-Perot (CFBG-FP) interferometer is used to perform nanostrain direct current (DC) measurement. The FP cavity is obtained between the chirp grating and the reflection at the end face of the fiber. The interferometer presents an aperiodic fringe pattern due to the chirp behavior of the FBG. For nanostrain measurement, long and short period fringe pattern wavelengths are analyzed using a laser optical power in the fringe slope region.

2. Experimental results

The experimental setup is shown in Fig. 1. A narrow linewidth laser with an optical power of −10 dBm with bandwidth of 40 MHz, and an output power stability of less than or equal to 5 pm is used to illuminate the CFBG-FP. The inset in Fig. 2 shows the laser spectrum, centered at 1553.6 nm. An optical circulator and a photodetector (EXFO IQ 203) were used to interrogate the sensing head. A signal processing was used to acquire the reflected optical power, which was detected by the photodetector.

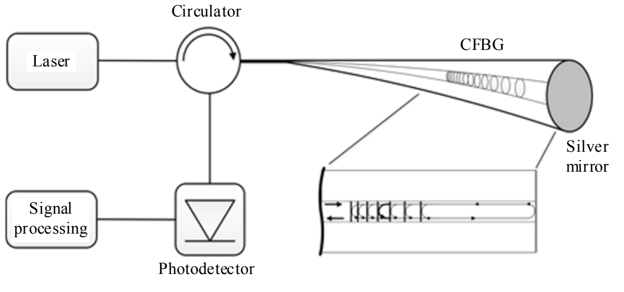

Fig. 1 Experimental setup of the nanostrain sensor based on chirped Bragg grating interferometer.

The sensing head was formed by a chirped Bragg grating, with a chirp of 0.4 nm/cm and a length of 25 mm. The CFBG was written in a standard single mode fiber (SMF 28) by the phase mask technique with an ultraviolet (UV) laser at 248 nm.

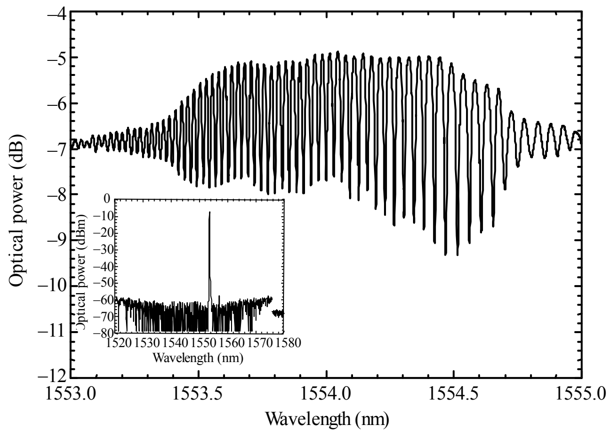

Fig. 2 Spectral response of the chirped Bragg grating FP interferometer (inset figure: laser spectrum).

The spacing between the chirped Bragg grating and the cleaved tip of the fiber formed the FP cavity. A silver mirror was coated at the tip of the fiber end face, in order to increase the pattern fringes visibility. In this case, an aperiodic pattern fringe is expected, due to the different optical paths between the fiber end face and the chirp periodicity of the Bragg grating. Figure 2 presents the spectral response of the interferometer. This spectrum was acquired using an optical spectrum analyzer (OSA) with a resolution of 10 pm. There is no constant variation of the visibility along the spectrum, even though it should be expected. This discrepancy is due to the limitation of the OSA resolution for lower wavelengths measurement (blue shift). The fringe visibility average value is 45% and the FP cavity length is 34 mm. In order to obtain strain variations smaller than 1 με, using a translation stage with a resolution of 1 μm, it is required to use a fiber length longer than 1 m. In this experiment, the length chosen was about 2 m, which allowed a strain step of 470 nε. The characterization of the sensing head was done using two different laser wavelengths, one at

1553.6 nm and the other at 1554.5 nm. These correspond to the short and long period fringe regions, where the wavelength spacings are 0.02 nm and 0.05 nm, respectively. Figure 3 shows the laser peak variation for different strain values at a constant wavelength of 1553.6 nm. When strain is applied to the CFBG-FP cavity, the optical path between the grating and the fiber end face increases and the fringe pattern shifts towards longer wavelengths (red shift). In this case, the optical power of the laser peak decreases in the linear slope region of the fringe pattern. In relation to wavelength shift due to the applied strain, sensitivities of 0.1 pm/με and 0.4 pm/με were obtained for the smaller and larger period fringe regions of the CFBG spectrum, respectively. Figure 4 exhibits the relation between the laser optical

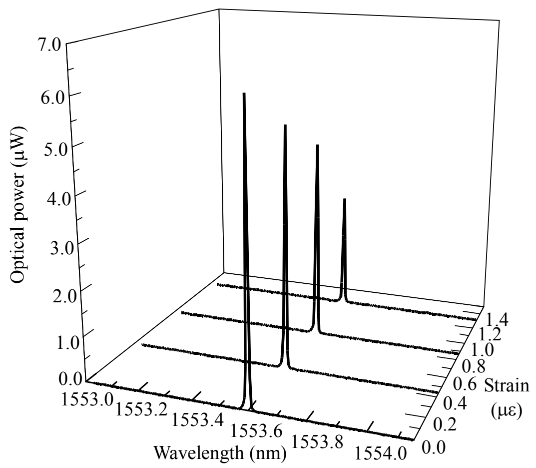

Fig. 3 Optical power spectrum of the laser when strain is applied to the interferometer.

power and the strain measurement. As it can be seen, the laser optical power presents the same behavior as the FP cavity spectral response. From 0 to 16 με, two linear regions can be identified. These linear regions are interesting for nanostrain measurement, since their range is between 0 and 2 με. Figure 5 presents the sensing head response to applied strain, in the region between 0 and 2 με (short period fringe) and from 0 to 5 με (long period fringe). The sensitivities obtained are –5.48 μW/με and –2.87 μW/με, respectively. All measurements were taken at a room temperature of 24 ℃.

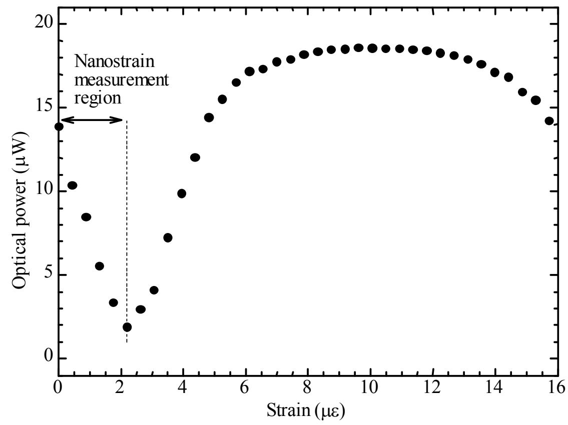

Fig. 4 Optical power variation when the strain is applied.

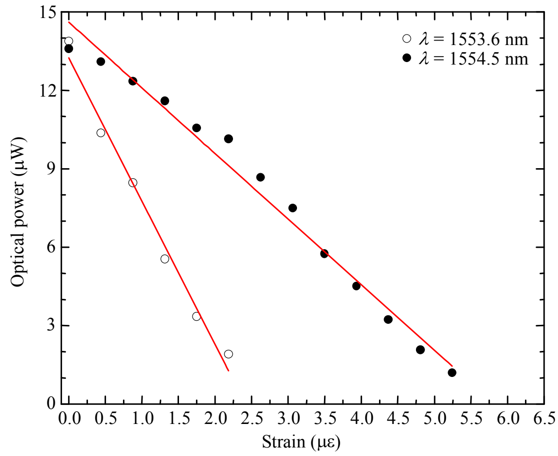

Fig. 5 Sensitivity of the chirped Bragg grating FP interferometer for two different laser positions.

The resolution of the sensor system for strain measurement was also evaluated. The parameter output power P_{out} of the laser was measured during a step strain applied to the CFBG. The minimum value of strain, $\delta\varepsilon$, that the system is able to discriminate is given by:

$$\delta\varepsilon = \frac{2\left(\sigma_{P\mathrm{out}}\Delta\varepsilon_{(\mathrm{step})}\right)}{\Delta P_{\mathrm{out}}} \tag{1}$$

where $\sigma_{P\mathrm{out}}$ is the maximum standard deviation of P_{out} for strain measurement. In order to determine the system resolution, a step of 875 nε was applied for 30 seconds, and for DC strain variation, a resolution of 70 nε was obtained (Fig. 6).

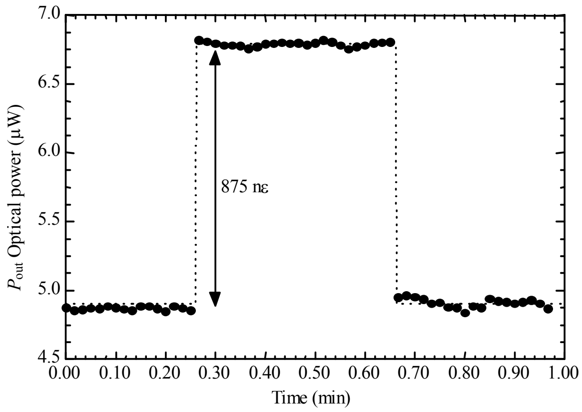

Fig. 6 Strain resolution of the chirped Bragg grating FP interferometer.

3. Conclusions

In summary, a simple chirped fiber Bragg grating Fabry-Perot interferometer was used to measure DC nanostrain. The FP cavity was created between the chirp grating and the reflection of the fiber end face. An aperiodic interference was verified due to the chirp behavior of the FBG. The optical power variation of the FP cavity was analyzed at 1553.6 nm and 1554.5 nm, when the sensing head was subjected to strain. The sensitivities calculated were –5.48 μW/με and –2.87 μW/με, for short and long period fringes, respectively. Due to the different sensitivities, using two lasers in the same CFBG, it is possible to perform quasi-distributed measurement, thus discriminating multiple physical parameters. This configuration presented a resolution of 70 nε, for the short period fringe. The main objective of this work was to analyze the behavior of this sensing head when it was subjected to strain variations. Nevertheless, by performing AC measurement, a resolution improvement should be expected.

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